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SPACE SHUTTLE ENGINEERING AND OPERATIONS SUPPORT

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MULTIPLE DIELECTRIC LAYER EFFECTS ON THE SPACE SHUTTLE ORBITER S-BAND QUAD ANTENNAS

ENGINEERING SYSTEMS ANALYSIS

(NASA-CR-147771) MULTIPLE DIELECTRIC LAYER EFFECTS ON THE SPACE SHUTTLE ORBITER S-BAND QUAD ANTENNAS (MCDONNELL-DOUGLAS TECHNICAL SERVICES) 41 P HC $4.00 CSCL 17B
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1.0 SUMMARY

In this study a mathematical tool is developed for evaluation of antenna radiation pattern effects on the Shuttle Orbiter S-Band Quad antennas. A ray optics approach is used which includes multiple internal reflections with special consideration to reflection from the metallic Orbiter skin. The study shows significant depolarization may occur as the angle from the normal increases. Also the effect of changing tile thickness on the beamwidth of the upper Quads versus the lower Quads results in a small increase in the lower Quad beamwidth compared with the beamwidth in the upper Quads. The results of this study may be used to minimize testing in the optimization and evaluation of the S-Band Quads and the computer tool developed in this study may be used to evaluate other Shuttle Orbiter antennas.

2.0 INTRODUCTION

The purpose of this study is to evaluate theoretically the effects of the dielectric materials which cover the S-Band Quad antennas on the Shuttle Orbiter. The antenna is assumed to be a point source and the ray optics method using multiple internal reflections to calculate the tranmission coefficient as a function of angle is used. Two thicknesses of material corresponding to the two upper and the two lower Quads are considered. In this study a total of 20 individual rays are considered to improve the accuracy of that obtained in an interim report (1.2-DN-B0403-004 dated November 21, 1976). The previous report included only 6 individual rays and showed more severe radiation pattern effects from the multiple layer dielectric thermal protection system. The results of this study may also be used to evaluate the radiation characteristics of other multiple dielectric covered antennas thus minimizing the need for testing to determine optimum design.

In this paper background information is given describing the specific problem and previous work. The theoretical basis for the solution and the formulation used are then described. This is followed by the computer results and conclusions.

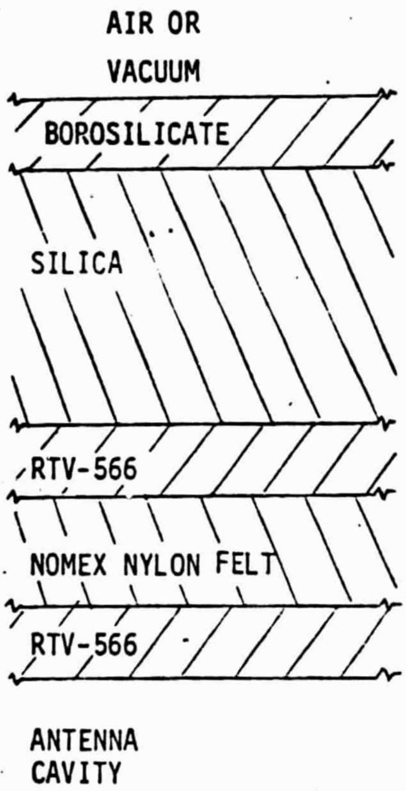
3.0 DISCUSSION

This section contains (1) background information, (2) the theoretical basis for the ray optics technique and (3) a description of the equations used in the computer formulation.

3.1 Background

Traditional solutions for dielectric and radome covered antennas have involved the use of plane wave transmission theory through multiple dielectric layers (References A, B and C). More recent exact solutions have involved the Fourier transform technique for a single dielectric layer with an assumed aperture distribution (References D and E). Another method considered was the method of moments (Reference F), which utilizes mutual coupling to produce the antenna pattern. Both the Fourier transform technique and method of moments have been developed only for single dielectric cases. Because of simplicity and adaptability, it was decided to pursue a modified version of the plane wave transmission theory including multiple internal reflections and the effect of the ground plane reflection. Previous methods have not considered the ground plane reflection.

The thermal protection system (TPS) consists of Lockheed LI-900 tiles having dimensions of 6 inches by 6 inches and varying thicknesses. The antenna TPS interface is shown in Figure 1. The multiple dielectric



	LAYER DESIGNATION	LAYER THICKNESS	DIELECTRIC CONSTANT	LOSS TANGENT
BOROSILICATE	5	.010"	4.8	.003
SILICA	4	.405" (upper) 1.86" (lower)	1.17	.0016
RTV-566	3	.015"	4.0	.005
NOMEX NYLON FELT	2	.250"	3.6	.040
RTV-566	1	.015"	4.0	.005

FIGURE 1. MULTIPLE LAYER TPS ANTENNA INTERFACE CONFIGURATION

layers are seen to consist of an RTV-566 layer, Nomex Nylon (felt), a second layer of RTV-566, the silica portion of the TPS tile and a waterproof coating of borosilicate. The most significant part of the dielectric interface is the LI-900 tile which has a thickness of 1.68-2.15 inches near the two lower Quad antennas and 0.41-0.42 inches near the two upper Quad antennas. The tiles are placed on the metal skin of the Orbiter in an alternating fashion similar to a house brick matrix. The spacing between the tiles is .060 inches and the walls of the tiles are coated with borosilicate. Since the thickness of the borosilicate coating and the spacing between tiles is small compared with a wavelength at S-Band, the effects of the walls are not incorporated in this study. The basic techniques of calculating the angles of refraction, transmission coefficients and reflection coefficients are developed in this study and later could be applied to wall effects which may be appreciable at Ku-Band and higher frequencies.

3.2 Theoretical Basis

This study assumes an isotropic hemispherical radiator from a point source with individual rays incident upon five dielectric materials as shown in Figure 1. The angles of refraction are determined by Snell's law such that

$$\frac{\sin \Theta_i}{\sin \Theta_j} = \frac{\sqrt{\varepsilon_j}}{\sqrt{\varepsilon_i}} \qquad (1)$$

where Θ_i is the input angle of incidence measured from the internal normal in the i^{th} dielectric

Θ_j is the output angle measured from the internal normal in the j^{th} dielectric

ε_i is the relative dielectric constant in the i^{th} dielectric

ε_j is the relative dielectric constant in the j^{th} dielectric

Equation (1) may be rewritten in the form below to calculate successive refraction angles such that

$$\Theta_j = \arcsin\left(\frac{\sqrt{\varepsilon_i}}{\sqrt{\varepsilon_j}} \cdot \sin \Theta_i\right) \qquad (2)$$

The tabulation in Figure 2 shows the angles of refraction through each layer of dielectric material. The input angle is designated as Θ_0. It is noted that the input and output angles are the same since $\varepsilon_0 = \varepsilon_6 = 1.0$. A special case exists when the ray is passing from a material of high dielectric constant to one of low dielectric constant such that complete internal reflection occurs. This happens when the incident angle is equal to or greater than the critical angle (Θ_c) where

$$\Theta_{ic} = \arcsin\left(\frac{\sqrt{\varepsilon_j}}{\sqrt{\varepsilon_i}}\right) \qquad (3)$$

The critical angles associated with the high dielectric constant materials are found to be

Θ_{1c} = 71.57° (RTV-566)
Θ_{3c} = 32.74° (RTV-566)
Θ_{5c} = 27.15° (Coating)

θ_0	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6
1.00	.50	.53	.50	.92	.46	1.00
2.00	1.00	1.05	1.00	1.85	.91	2.00
3.00	1.50	1.58	1.50	2.77	1.37	3.00
4.00	2.00	2.11	2.00	3.70	1.82	4.00
5.00	2.50	2.63	2.50	4.62	2.28	5.00
6.00	3.00	3.16	3.00	5.55	2.73	6.00
7.00	3.49	3.68	3.49	6.47	3.19	7.00
8.00	3.99	4.21	3.99	7.39	3.64	8.00
9.00	4.49	4.73	4.49	8.32	4.09	9.00
10.00	4.98	5.25	4.98	9.24	4.55	10.00
11.00	5.47	5.77	5.47	10.16	5.00	11.00
12.00	5.97	6.29	5.97	11.08	5.45	12.00
13.00	6.46	6.81	6.46	12.00	5.89	13.00
14.00	6.95	7.33	6.95	12.92	6.34	14.00
15.00	7.44	7.84	7.44	13.84	6.78	15.00
16.00	7.92	8.35	7.92	14.76	7.23	16.00
17.00	8.41	8.86	8.41	15.68	7.67	17.00
18.00	8.89	9.37	8.89	16.60	8.11	18.00
19.00	9.37	9.88	9.37	17.52	8.55	19.00
20.00	9.85	10.38	9.85	18.43	8.98	20.00
21.00	10.32	10.89	10.32	19.35	9.41	21.00
22.00	10.80	11.39	10.80	20.26	9.85	22.00
23.00	11.27	11.88	11.27	21.18	10.27	23.00
24.00	11.73	12.38	11.73	22.09	10.70	24.00
25.00	12.20	12.87	12.20	23.00	11.12	25.00
26.00	12.66	13.36	12.66	23.91	11.54	26.00
27.00	13.12	13.84	13.12	24.82	11.96	27.00
28.00	13.58	14.33	13.58	25.72	12.37	28.00
29.00	14.03	14.80	14.03	26.63	12.78	29.00
30.00	14.48	15.28	14.48	27.53	13.19	30.00
31.00	14.92	15.75	14.92	28.43	13.60	31.00
32.00	15.36	16.22	15.36	29.33	14.00	32.00
33.00	15.80	16.68	15.80	30.23	14.39	33.00
34.00	16.24	17.14	16.24	31.13	14.79	34.00
35.00	16.67	17.60	16.67	32.02	15.18	35.00
36.00	17.09	18.05	17.09	32.92	15.56	36.00
37.00	17.51	18.49	17.51	33.81	15.94	37.00
38.00	17.93	18.93	17.93	34.69	16.32	38.00
39.00	18.34	19.37	18.34	35.58	16.69	39.00
40.00	18.75	19.80	18.75	36.46	17.06	40.00
41.00	19.15	20.22	19.15	37.34	17.42	41.00
42.00	19.55	20.65	19.55	38.21	17.78	42.00
43.00	19.94	21.07	19.94	39.09	18.14	43.00
44.00	20.32	21.48	20.32	39.96	18.49	44.00
45.00	20.70	21.88	20.70	40.82	18.83	45.00
46.00	21.08	22.28	21.08	41.68	19.17	46.00
47.00	21.45	22.67	21.45	42.54	19.50	47.00
48.00	21.81	23.06	21.81	43.40	19.83	48.00
49.00	22.17	23.44	22.17	44.25	20.15	49.00
50.00	22.52	23.81	22.52	45.09	20.47	50.00
51.00	22.87	24.18	22.87	45.93	20.79	51.00
52.00	23.20	24.54	23.20	46.76	21.08	52.00
53.00	23.54	24.89	23.54	47.59	21.38	53.00
54.00	23.86	25.24	23.86	48.41	21.67	54.00
55.00	24.18	25.58	24.18	49.23	21.96	55.00
56.00	24.49	25.91	24.49	50.04	22.23	56.00
57.00	24.79	26.23	24.79	50.84	22.51	57.00
58.00	25.09	26.55	25.09	51.63	22.77	58.00
59.00	25.38	26.86	25.38	52.42	23.03	59.00
60.00	25.66	27.16	25.66	53.19	23.28	60.00
61.00	25.93	27.45	25.93	53.96	23.53	61.00
62.00	26.20	27.73	26.20	54.71	23.77	62.00
63.00	26.46	28.01	26.46	55.46	24.00	63.00
64.00	26.71	28.28	26.71	56.19	24.22	64.00
65.00	26.95	28.53	26.95	56.92	24.44	65.00
66.00	27.18	28.78	27.18	57.63	24.64	66.00
67.00	27.40	29.02	27.40	58.32	24.84	67.00
68.00	27.62	29.25	27.62	59.00	25.04	68.00
69.00	27.83	29.47	27.83	59.67	25.22	69.00
70.00	28.02	29.69	28.02	60.31	25.40	70.00
71.00	28.21	29.89	28.21	60.94	25.57	71.00
72.00	28.39	30.08	28.39	61.55	25.73	72.00
73.00	28.56	30.27	28.56	62.14	25.88	73.00
74.00	28.73	30.44	28.73	62.71	26.02	74.00
75.00	28.88	30.61	28.88	63.25	26.16	75.00
76.00	29.02	30.76	29.02	63.77	26.29	76.00
77.00	29.16	30.90	29.16	64.26	26.41	77.00
78.00	29.28	31.03	29.28	64.73	26.52	78.00
79.00	29.39	31.16	29.39	65.16	26.62	79.00
80.00	29.50	31.27	29.50	65.57	26.71	80.00
81.00	29.59	31.37	29.59	65.94	26.80	81.00
82.00	29.68	31.46	29.68	66.28	26.87	82.00
83.00	29.75	31.54	29.75	66.58	26.94	83.00
84.00	29.82	31.61	29.82	66.84	27.00	84.00
85.00	29.87	31.67	29.87	67.07	27.05	85.00
86.00	29.92	31.72	29.92	67.26	27.09	86.00
87.00	29.95	31.76	29.95	67.40	27.12	87.00
88.00	29.98	31.78	29.98	67.51	27.14	88.00
89.00	29.99	31.80	29.99	67.57	27.15	89.00
ANTENNA CAVITY	RTV-566	FELT	RTV-566	SILICA	COATING	AIR OR VACUUM

FIGURE 2. TABULATION OF ANGLES OF REFRACTION

As may be noted in Figure 2 none of the previous critical angles are exceeded. If, however, the dielectric constant of the material at the antenna surface is significantly greater than air ($\varepsilon_o = 1$), then complete internal reflection will exist at angles equal to and greater than the critical angle.

The second factor to be considered is that of the phase delay which occurs in each dielectric material. From geometrical and electrical considerations the phase delay in the n^{th} material is given by

$$\Delta\phi_n = \frac{2\pi \quad f \quad \sqrt{\varepsilon_n}}{C} \times \frac{X_n}{\cos \Theta_n} \qquad (4)$$

where $\Delta\phi_n$ is the phase delay in radians

f is the frequency in MHz (assume 2200)

ε_n is the relative dielectric constant of the n^{th} dielectric

X_n is the thickness of the n^{th} dielectric

C is the speed of light (assume 11808 megainches/sec.)

Θ_n is the angle of refraction in the n^{th} dielectric

The largest phase delay takes place in the silica part of the TPS and ranges from 135° to 353.7° for the two lower Quads and from 29.4° to 77° for the two upper Quads. The incidence angles for the above delays range between 0° and 89°. The delay in the felt material ranges from 31.8° to 37.4° for the above conditions and the delays in the RTV-566 and the borosilicate coating are less than 2.3° degrees. In general, single layer phase shifts of 180°, 360° etc. will provide maximum transmission and those of 90°, 270° etc. will provide minimum transmission when internal reflections are considered.

The next factor considered is the transmission coefficient for perpendicular polarization which is the ratio of the transmitted electric field to the incident electric field given by (Reference G)

$$\hat{\tau}_{ij_\perp} = \frac{\hat{E}_{j_\perp T}}{\hat{E}_{i_\perp inc}} = \frac{2\sqrt{\hat{\varepsilon}_{ci}}\,\cos\Theta_i}{\sqrt{\hat{\varepsilon}_{ci}}\,\cos\Theta_i + \sqrt{\hat{\varepsilon}_{cj}}\,\cos\Theta_j} \qquad (5)$$

where $\hat{\tau}_{ij_\perp}$ is the transmission coefficient for perpendicular polarization which is a complex number

$\hat{E}_{j_\perp T}$ is the transmitted field which is perpendicular to the plane of propagation

$\hat{E}_{i_\perp inc}$ is the incident field which is perpendicular to the plane of propagation

$\hat{\varepsilon}_i$ is the relative complex permittivity in the i^{th} material

$\hat{\varepsilon}_j$ is the relative complex permittivity in the j^{th} material

Θ_i and Θ_j - input and output angles measured from their respective normals.

The relative complex permittivity may be expressed as

$$\hat{\varepsilon}_{cn} = \varepsilon_n - j\,\varepsilon_n \tan\delta_n \qquad (6)$$

where ε_n is the relative dielectric constant in the n^{th} material

$\tan \delta_n$ is the loss tangent in the n^{th} dielectric

For parallel polarization the transmission coefficient is given by (Reference G)

$$\hat{\tau}_{ij\parallel} = \frac{2\sqrt{\hat{\varepsilon}_{ci}}\ \cos \Theta_i}{\sqrt{\hat{\varepsilon}_{ci}}\ \cos \Theta_j + \sqrt{\hat{\varepsilon}_{cj}}\ \cos \Theta_i} \tag{7}$$

where $\hat{\tau}_{ij\parallel}$ is the ratio of the transmitted electric field in j^{th} medium to the incident electric field in the i^{th} medium which is parallel to the plane of propagation. Other variables are similar to those associated with Equations (5) and (6).

The expression for the reflection coefficient $\hat{r}_{ij_\perp}$ in the i^{th} dielectric from the j^{th} dielectric is given by (Reference G)

$$\hat{r}_{ij_\perp} = \frac{\hat{E}_{ij\perp\, ref}}{\hat{E}_{i_\perp inc}} = \frac{\sqrt{\hat{\varepsilon}_{ci}}\ \cos \Theta_i - \sqrt{\hat{\varepsilon}_{cj}}\ \cos \Theta_j}{\sqrt{\hat{\varepsilon}_{ci}}\ \cos \Theta_i + \sqrt{\hat{\varepsilon}_{cj}}\ \cos \Theta_j} \tag{8}$$

where $\hat{E}_{i_\perp inc}$ is the incident electric field in the i^{th} medium with perpendicular polarization and $\hat{E}_{ij_\perp ref}$ is the reflected electric field in the i^{th} medium with perpendicular polarization. Other variables are defined in Equations (5) and (6).

For parallel polarization the reflection coefficient is given by (Reference G)

$$\hat{r}_{ij\parallel} = \frac{\hat{E}_{ij\parallel ref}}{\hat{E}_{i\parallel inc}} = \frac{\sqrt{\hat{\varepsilon}_{ci}}\cos\Theta_j - \sqrt{\hat{\varepsilon}_{cj}}\cos\Theta_i}{\sqrt{\hat{\varepsilon}_{ci}}\cos\Theta_j + \sqrt{\hat{\varepsilon}_{cj}}\cos\Theta_i} \qquad (9)$$

It is interesting to note that parallel polarization has associated with it an angle where the reflection coefficient becomes zero called the Brewster angle or the polarizing angle.

This angle is given by

$$\Theta_{iB} = \tan^{-1}\sqrt{\frac{\varepsilon_j}{\varepsilon_i}} \qquad (10)$$

The Brewster angles for the S-Band Quad dielectric layers are found to be

$\Theta_{0B} = 63.43°$ $\Theta_{3B} = 28.41°$

$\Theta_{1B} = 43.49°$ $\Theta_{4B} = 63.72°$

$\Theta_{2B} = 46.51°$ $\Theta_{5B} = 24.53°$

The preceeding refraction angles correspond to reflection angles at which the internal reflected field will only be perpendicularly polarized for each respective dielectric.

Another factor to be considered is the attenuation in each dielectric material which is expressed for a low loss dielectric ($\tan\delta \ll 1$) as (Reference H)

$$\alpha_n = \frac{\pi f \sqrt{\varepsilon_n}\, X_n \tan(\delta_n)}{C \cos\Theta_{in}} \qquad (11)$$

where

α_n	is in Nepers
f	is the frequency in MHZ
ε_n	is the dielectric constant in the n^{th} dielectric
X_n	is the thickness in inches of the n^{th} dielectric
$\tan(\delta_n)$	is the loss tangent of the n^{th} dielectric
C	is the speed of light in megainches/sec.
θ_i	is the angle of incidence in the n^{th} dielectric

The actual attenuation of the electric field is given by

$$ATTn = e^{-\alpha_n} \tag{12}$$

It should be pointed out that the power transmission coefficient for a circularly polarized incident ray may be obtained from the following relationship

$$|\hat{T}|^2 = \left|\frac{\hat{T}_\perp + \hat{T}_\parallel}{2}\right|^2 \tag{13a}$$

or

$$|\hat{T}|^2 = 1/4 \{|\hat{T}_\parallel|^2 + |\hat{T}_\perp|^2 + 2\,|\hat{T}_\perp||\hat{T}_\parallel| \cos\delta_\rho\} \tag{13b}$$

where $\hat{T}_\parallel$ is the overall transmission coefficient for parallel polarization

$\hat{T}_\perp$ is the overall transmission coefficient for perpendicular polarization

δ_ρ is the difference in phase between perpendicular and the parallel overall transmission coefficients.

3.3 Formulation

The computer formulation to calculate the transmission coefficient for circular polarization (as generated by Orbiter S-Band Quad Elements) involves extensive use of the previously developed formulas. The transmission coefficient for a direct ray may be written in the following notation for perpendicular polarization

$$\begin{aligned} \hat{\tau}_{06_\perp} &= \hat{\tau}_{01_\perp}\,\hat{\tau}_{12_\perp}\,\hat{\tau}_{23_\perp}\,\hat{\tau}_{34_\perp}\,\hat{\tau}_{45_\perp}\,\hat{\tau}_{56_\perp} \\ &\times e^{-\alpha_1}\,e^{-\alpha_2}\,e^{-\alpha_3}\,e^{-\alpha_4}\,e^{-\alpha_5} \qquad (14) \\ &\times e^{-j\,(\Delta\phi_1 + \Delta\phi_2 + \Delta\phi_3 + \Delta\phi_4 + \Delta\phi_5)} \end{aligned}$$

where $\Delta\phi$, τ and α are computed from Equations (4), (5) and (11). For parallel polarization the symbol "$\perp$" is replaced by "$\parallel$". The $\hat{\tau}$'s represent complex transmission coefficients, $e^{-\alpha}$'s represent attenuations and $e^{-j\Delta\phi}$'s represent phase delays in passing through each dielectric. The subscripts designate the following

0 for the antenna cavity
1 for the inner RTV bond
2 for the felt (strain isolation pad)
3 for the outer RTV bond
4 for the silica portion of the tile
5 for the borosilicate (waterproof coating)
6 for the air or vacuum region outside the borosilicate coating

Since there exists the possibility of an infinite number of internal reflections and subsequent retransmissions, the transmission and reflection coefficient magnitudes for each interface were determined in order to evaluate only the most significant reflections and retransmissions. A matrix showing some of the data is given in Figure 3 for a total tile thickness of 1.87 inches with the weatherproof coating. The reflection and transmission coefficient magnitudes are included as well as the phase delay in degrees and the electric field attenuation factors. It is observed that some transmission coefficient magnitudes exceed 1.0 in going from a material of high dielectric constant (low impedance) to one of lower dielectric constant (higher impedance). An analogous result occurs when a transmission line of low impedance is connected to one of high impedance in which the transmitted voltage may double in magnitude in the high impedance line. From Figure 3 it is observed that the reflection coefficient magnitudes for $\hat{r}_{12}$ and $\hat{r}_{23}$ are quite small (less than .04) and that the reflection coefficient magnitudes for $\hat{r}_{34}$, $\hat{r}_{45}$ and $\hat{r}_{56}$ are somewhat more significant being on the order of .3 for $\Theta = 1°$. Internal reflections resulting from $\hat{r}_{56}$, $\hat{r}_{45}$ and $\hat{r}_{34}$ are shown in equations (15), (16) and (17).

0 ANTENNA CAVITY	1 RTV-566	2 NOMEX FELT	3 RTV-566	4 SILICA	5 COATING	6 AIR OR VACUUM
θ_0 = 1.0° T01⊥ = .67 T01∥ = .67	θ_1 = .5° $\Delta\phi_1$ = 2.0° T12⊥ = 1.03 T12∥ = 1.03 R12⊥ = .03 R12∥ = .03 T21⊥ = .97 T21∥ = .97 ATT1 = 1.00	θ_2 = .5° $\Delta\phi_2$ = 31.8° T23⊥ = .97 T23∥ = .97 R23⊥ = .03 R23∥ = .03 T32⊥ = 1.03 T32∥ = 1.03 ATT2 = .99	θ_3 = .5° $\Delta\phi_3$ = 2.0° T34⊥ = 1.30 T34∥ = 1.30 R34⊥ = .30 R34∥ = .30 T43⊥ = .70 T43∥ = .70 ATT3 = 1.00	θ_4 = .9° $\Delta\phi_4$ = 135.0° T45⊥ = .66 T45∥ = .66 R45⊥ = .34 R45∥ = .34 T54⊥ = 1.34 T54∥ = 1.34 ATT4 = 1.00	θ_5 = .5° $\Delta\phi_5$ = 1.5° T56⊥ 1.37 T56∥ 1.37 R56⊥ .37 R56∥ .37 ATT5 1.00	θ_6 = 1.0° T06⊥ = .7797 T06∥ = .7798
θ_0 = 15.0° T01⊥ = .66 T01∥ = .66	θ_1 = 7.4° $\Delta\phi_1$ = 2.0° T12⊥ = 1.03 T12∥ = 1.03 R12⊥ = .03 R12∥ = .03 T21⊥ = .97 T21∥ = .97 ATT1 = 1.00	θ_2 = 7.8° $\Delta\phi_2$ = 32.1° T23⊥ = .97 T23∥ = .97 R23⊥ = .03 R23∥ = .03 T32⊥ = 1.03 T32∥ = 1.03 ATT2 = .99	θ_3 = 7.4° $\Delta\phi_3$ = 2.0° T34⊥ = 1.31 T34∥ = 1.32 R34⊥ = .31 R34∥ = .29 T43⊥ = .69 T43∥ = .70 ATT3 = 1.00	θ_4 = 13.8° $\Delta\phi_4$ = 139.0° T45⊥ = .65 T45∥ = .66 R45⊥ = .35 R45∥ = .33 T54⊥ = 1.35 T54∥ = 1.36 ATT4 = 1.00	θ_5 = 6.8° $\Delta\phi_5$ = 1.5° T56⊥ = 1.39 T56∥ = 1.40 R56⊥ = .39 R56∥ = .36 ATT5 = 1.00	θ_6 = 15.0° T06⊥ = .7617 T06∥ = .7873
θ_0 = 30.0° T01⊥ = .62 T01∥ = .69	θ_1 = 19.5° $\Delta\phi_1$ = 2.1° T12⊥ = 1.03 T12∥ = 1.03 R12⊥ = .03 R12∥ = .03 T21⊥ = .97 T21∥ = .97 ATT1 = 1.00	θ_2 = 15.3° $\Delta\phi_2$ = 33.0° T23⊥ = .97 T23∥ = .97 R23⊥ = .03 R23∥ = .03 T32⊥ = 1.03 T32∥ = 1.03 ATT2 .99	θ_3 = 19.5° $\Delta\phi_3$ = 2.1° T34⊥ = 1.34 T34∥ = 1.37 R34⊥ = .34 R34∥ = .26 T43⊥ = .66 T43∥ = .68 ATT3 = 1.00	θ_4 = 27.5° $\Delta\phi_4$ = 152.2° T45⊥ = .62 T45∥ = .64 R45⊥ = .38 R45∥ = .30 T54⊥ = 1.38 T54∥ = 1.42 ATT4 = 1.00	θ_5 = 13.2° $\Delta\phi_5$ = 1.5° T56⊥ = 1.42 T56∥ = 1.49 R56⊥ = .42 R56∥ = .32 ATT5 = 1.00	θ_6 = 30.0° T06⊥ = .7189 T06∥ = .8260
θ_0 = 50.0° T01⊥ = .52 T01∥ = .58	θ_1 = 22.5° $\Delta\phi_1$ = 2.2° T12⊥ = 1.03 T12∥ = 1.03 R12⊥ = .03 R12∥ = .02 T21⊥ = .97 T21∥ = .97 ATT1 = 1.00	θ_2 = 23.8° $\Delta\phi_2$ = 34.6° T23⊥ = .97 T23∥ = .97 R23⊥ = .03 R23∥ = .02 T32⊥ = 1.03 T32∥ = 1.03 ATT2 = .99	θ_3 = 22.5° $\Delta\phi_3$ = 2.2° T34⊥ = 1.42 T34∥ = 1.53 R34⊥ = .42 R34∥ = .17 T43⊥ = .58 T43∥ = .63 ATT3 = 1.00	θ_4 = 45.1° $\Delta\phi_4$ = 191.1° T45⊥ = .54 T45∥ = .60 R45⊥ = .46 R45∥ = .21 T54⊥ = 1.46 T54∥ = 1.60 ATT4 = 1.00	θ_5 = 20.5° $\Delta\phi_5$ = 1.6° T56⊥ = 1.52 T56∥ = 1.75 R56⊥ = .52 R56∥ = .20 ATT5 = 1.00	θ_6 = 50.0° T06⊥ = .5939 T06∥ = .9169
θ_0 = 70.0° T01⊥ = .32 T01∥ = .99	θ_1 = 28.0° $\Delta\phi_1$ = 2.3° T12⊥ = 1.03 T12∥ = 1.03 R12⊥ = .04 R12∥ = .02 T21⊥ = .97 T21∥ = .97 ATT1 = 1.00	θ_2 = 29.7° $\Delta\phi_2$ = 36.6 T23⊥ = .97 T23∥ = .97 R23⊥ = .04 R23∥ = .02 T32⊥ = 1.03 T32∥ = 1.03 ATT2 = .99	θ_3 = 28.0° $\Delta\phi_3$ = 2.3° T34⊥ = 1.53 T34∥ = 1.82 R34⊥ = .53 R34∥ = .02 T43⊥ = .47 T43∥ = .55 ATT3 = 1.00	θ_4 = 60.3° $\Delta\phi_4$ = 272.5° T45⊥ = .43 T45∥ = .52 R45⊥ = .57 R45∥ = .05 T54⊥ = 1.57 T54∥ = 1.92 ATT4 = 1.00	θ_5 = 25.4° $\Delta\phi_5$ = 1.6° T56⊥ = 1.71 T56∥ = 2.40 R56⊥ = .71 R56∥ = .09 ATT5 1.00	θ_6 = 70.0° T06⊥ = .3559 T06∥ = .9679

PHASE DELAYS, ATTENUATIONS AND DIRECT TRANSMISSION COEFFICIENTS APPLY TO LOWER QUADS ONLY.

FIGURE 3. TRANSMISSION AND REFLECTION COEFFICIENT MAGNITUDES AND OTHER DATA

$$
\begin{aligned}
\hat{T}_{R56_\perp} = \; & \hat{\tau}_{01_\perp}\,\hat{\tau}_{12_\perp}\,\hat{\tau}_{23_\perp}\,\hat{\tau}_{34_\perp}\,\hat{\tau}_{45_\perp}\,\hat{\tau}_{56_\perp} \\
& \times\,\hat{\tau}_{54_\perp}\,\hat{\tau}_{43_\perp}\,\hat{\tau}_{32_\perp}\,\hat{\tau}_{21_\perp}\,\hat{r}_{10_\perp}\,\hat{\tau}_{12_\perp} \\
& \times\,\hat{\tau}_{23_\perp}\,\hat{\tau}_{34_\perp}\,\hat{\tau}_{45_\perp}\,\hat{\tau}_{56_\perp}\,e^{-3\,(\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 + \alpha_5)} \\
& \times\,e^{-j3(\Delta\phi_1 + \Delta\phi_2 + \Delta\phi_3 + \Delta\phi_4 + \Delta\phi_5)}
\end{aligned}
\tag{15}
$$

$$
\begin{aligned}
\hat{T}_{R45_\perp} = \; & \hat{\tau}_{01_\perp}\,\hat{\tau}_{12_\perp}\,\hat{\tau}_{23_\perp}\,\hat{\tau}_{34_\perp}\,\hat{r}_{45_\perp}\,\hat{\tau}_{43_\perp}\,\hat{\tau}_{32_\perp}\,\hat{\tau}_{21_\perp}\,\hat{r}_{10} \\
& \times\,\hat{\tau}_{10_\perp}\,\hat{\tau}_{12_\perp}\,\hat{\tau}_{23_\perp}\,\hat{\tau}_{34_\perp}\,\hat{\tau}_{45_\perp}\,\hat{\tau}_{56_\perp} \\
& \times\,e^{-3(\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4)}\;e^{-\alpha_5} \\
& \times\,e^{-j\,3\,(\Delta\phi_1 + \Delta\phi_2 + \Delta\phi_3 + \Delta\phi_4)}e^{-j\Delta\phi_5}
\end{aligned}
\tag{16}
$$

$$
\begin{aligned}
\hat{T}_{R34_\perp} = \; & \hat{\tau}_{01_\perp}\,\hat{\tau}_{12_\perp}\,\hat{\tau}_{23_\perp}\,\hat{r}_{34_\perp}\,\hat{\tau}_{32_\perp}\,\hat{\tau}_{21_\perp}\,\hat{r}_{10_\perp} \\
& \times\,\tau_{01_\perp}\,\tau_{42_\perp}\,\tau_{23_\perp}\,\tau_{34_\perp}\,\tau_{45_\perp}\,\tau_{56_\perp} \\
& \times\,e^{-3(\alpha_1 + \alpha_2 + \alpha_3)}\;e^{-(\alpha_4 + \alpha_5)} \\
& \times\,e^{-j3\,(\Delta\phi_1 + \Delta\phi_2 + \Delta\phi_3)}\;e^{-j\,(\Delta\phi_4 + \Delta\phi_5)}
\end{aligned}
\tag{17}
$$

where $\hat{r}_{10_\perp} = -1$ for reflection from the metal skin of the Orbiter. Similar expressions for T_{R23} and T_{R12} may be written and the above equations for parallel polarization may be obtained by changing the subscript "$\perp$" to "$\parallel$". In addition to the preceeding internal reflections additional reflections are considered because of the significant magnitude of the reflection coefficients in layers 3, 4 and 5.

These include two rays which reflect from the borosilicate/air (or vacuum) interface $\hat{r}_{56}$ and from the silica/borosilicate interface $\hat{r}_{45}$ and which are then reflected from the silica/RTV interface $\hat{r}_{43}$ and transmitted forward. The equations for these two rays are

$$\begin{aligned} \hat{T}_{546_\perp} = {} & \hat{\tau}_{01_\perp} \hat{\tau}_{12_\perp} \hat{\tau}_{23_\perp} \hat{\tau}_{34_\perp} \hat{\tau}_{45_\perp} \hat{r}_{56_\perp} \\ & \times \hat{\tau}_{54_\perp} \hat{\tau}_{43_\perp} \hat{\tau}_{45_\perp} \hat{\tau}_{56_\perp} e^{-(\alpha_1 + \alpha_2 + \alpha_3)} \\ & \times e^{-3(\alpha_4 + \alpha_5)} e^{-j(\Delta\phi_1 + \Delta\phi_2 + \Delta\phi_3)} \\ & \times e^{-j3(\Delta\phi_4 + \Delta\phi_5)} \end{aligned} \tag{18}$$

$$\begin{aligned} \hat{T}_{446_\perp} = {} & \hat{\tau}_{01_\perp} \hat{\tau}_{12_\perp} \hat{\tau}_{23_\perp} \hat{\tau}_{34} \hat{r}_{45} \hat{r}_{43} \\ & \times \hat{\tau}_{45} \hat{\tau}_{56} e^{-(\alpha_1 + \alpha_2 + \alpha_3)} e^{-3\alpha_4} \\ & \times e^{-\alpha_5} e^{-j(\Delta\phi_1 + \Delta\phi_2 + \Delta\phi_3)} e^{-j3\Delta\phi_4} \\ & \times e^{-j\Delta\phi_5} \end{aligned} \tag{19}$$

It is noted that $\hat{r}_{43} = -\hat{r}_{34}$ and that the expression for parallel polarization may obtained replacing the "$\perp$" subscripts with "$\parallel$". Similar expressions may be written for $T_{556_\perp}$ which represents the transmission coefficient for a single internal reflection in the 5th layer as well as $T_{255_\perp}$ and $T_{355_\perp}$ which represents two and three internal reflections in the 5th layer. Also, expressions may be obtained for secondary reflections of three largest reflected rays $T_{R56\perp}$, $T_{R45\perp}$ and $\hat{T}_{R34\perp}$ from the 3/4, 4/5 and 5/6 interface as $\hat{T}_{X56\perp}$, $\hat{T}_{X45\perp}$ and $\hat{T}_{X34\perp}$. The last three transmission coefficients represent a total of 9 rays.

The composite transmission coefficient for 20 rays with perpendicular polarization becomes

$$\begin{aligned}\hat{T}_{\perp} = \; & \hat{T}_{06\perp} + \hat{T}_{R56\perp} + \hat{T}_{R45\perp} + \hat{T}_{R34\perp} + \hat{T}_{R23\perp} + \hat{T}_{R12\perp} \\ & + \hat{T}_{546\perp} + \hat{T}_{446\perp} + \hat{T}_{556\perp} + \hat{T}_{255\perp} + \hat{T}_{355\perp} \\ & + \hat{T}_{X56\perp} + \hat{T}_{X45\perp} + \hat{T}_{X34\perp}\end{aligned} \tag{20}$$

Parallel polarization is obtained by replacing the "$\perp$" symbols with "$\parallel$". The transmission coefficient for circular polarization becomes.

$$\hat{T}_{circ} = \frac{\hat{T}_{\perp} + \hat{T}_{\parallel}}{2} \tag{21}$$

4.0 RESULTS

This section describes pertinent results from the computer runs. A plot of the direct transmission coefficient magnitude for both perpendicular and parallel polarization is shown in Figure 4. These factors do not consider internal reflections and are presented only as an aid in understanding the complete effects of the multiple layer dielectric covering. It is observed that the perpendicular polarization coefficient is significantly smaller than the parallel coefficient which shows a tendency for the outgoing wave to have a predominant parallel polarization. If the input ray is assumed to have perfect circular polarization the axial ratio of an outgoing ray may be computed by the formula below assuming $\delta p = 0$.

$$\text{A. R.} = 20 \log \frac{|\hat{T}_{\parallel}|}{|\hat{T}_{\perp}|} \qquad (22)$$

At an angle of 50° the hypothetical axial ratio would be 3.77 dB. At 70° the hypothetical axial ratio becomes 8.7 dB.

The results of the computer run with the complete transmission coefficient including a dB factor for circular polarization are shown in Figure 5 and a plot of the results is given in Figure 6 for both the upper and lower Quad antennas. The dB factors represent pattern changes which would take place but do not necessarily represent a loss of energy since the pattern is redistributed and since energy reflected back into the antenna aperture is not specifically treated.

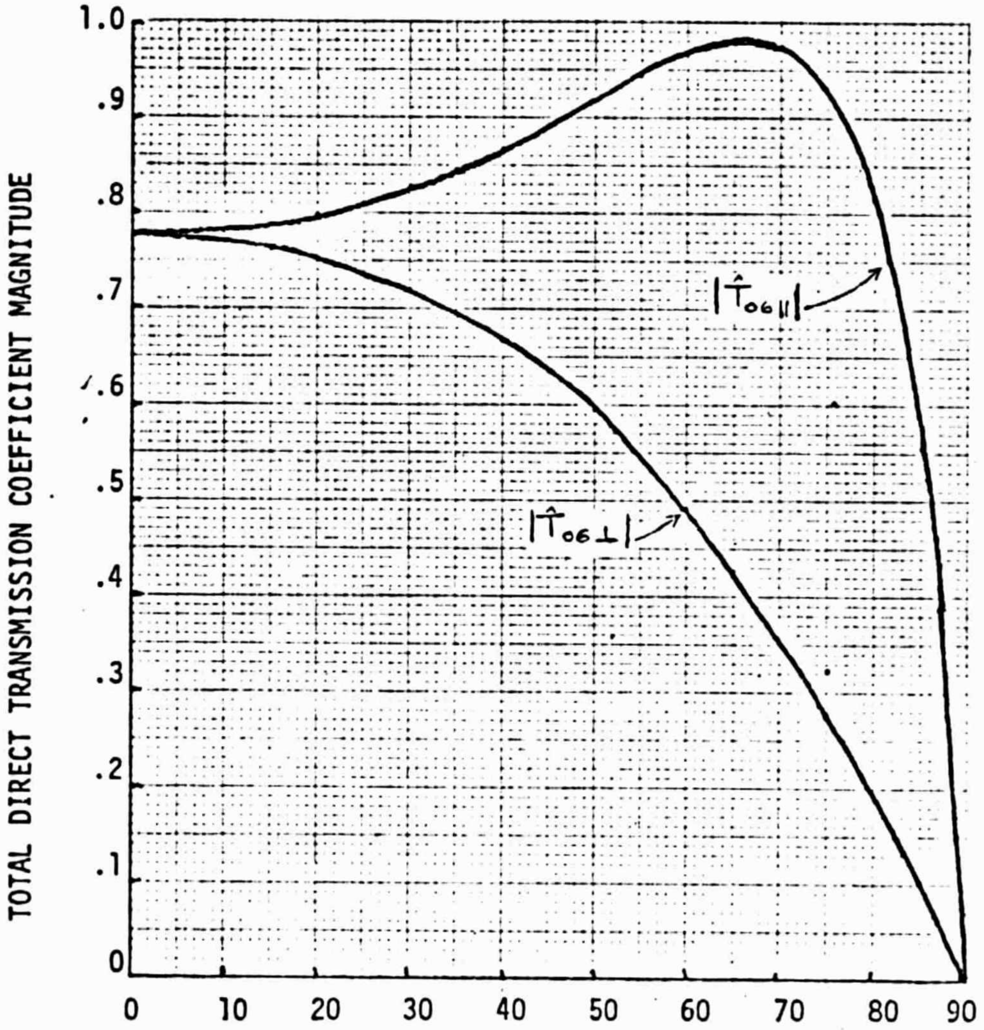


FIGURE 4 TOTAL DIRECT TRANSMISSION COEFFICIENT MAGNITUDE (NO INTERNAL REFLECTION)

```
                UPPER QUADS                                         LOWER QUADS

THETA    TPE     TPA    TCIR   TCIR(DB)      THETA    TPE     TPA    TCIR    TCIR(DB)

  1.0   .793    .793    .793    -2.020         1.0   .770    .771    .770    -2.265
  2.0   .792    .793    .793    -2.019         2.0   .770    .771    .771    -2.264
  3.0   .792    .793    .793    -2.019         3.0   .770    .771    .771    -2.262
  4.0   .792    .793    .793    -2.018         4.0   .770    .772    .771    -2.259
  5.0   .792    .794    .793    -2.018         5.0   .770    .772    .771    -2.255
  6.0   .791    .794    .793    -2.017         6.0   .770    .773    .772    -2.251
  7.0   .791    .795    .793    -2.016         7.0   .770    .774    .772    -2.246
  8.0   .790    .796    .793    -2.015         8.0   .770    .775    .773    -2.240
  9.0   .789    .797    .793    -2.014         9.0   .770    .777    .773    -2.233
 10.0   .789    .799    .793    -2.013        10.0   .770    .778    .774    -2.226
 11.0   .788    .799    .793    -2.011        11.0   .770    .780    .775    -2.218
 12.0   .787    .800    .793    -2.010        12.0   .770    .781    .775    -2.208
 13.0   .786    .801    .794    -2.008        13.0   .769    .783    .776    -2.198
 14.0   .785    .803    .794    -2.006        14.0   .769    .785    .777    -2.188
 15.0   .784    .804    .794    -2.005        15.0   .769    .788    .778    -2.176
 16.0   .782    .806    .794    -2.003        16.0   .769    .790    .780    -2.163
 17.0   .781    .808    .794    -2.001        17.0   .769    .792    .781    -2.150
 18.0   .779    .809    .794    -1.999        18.0   .769    .795    .782    -2.136
 19.0   .778    .811    .795    -1.997        19.0   .769    .798    .783    -2.121
 20.0   .776    .813    .795    -1.995        20.0   .769    .801    .785    -2.105
 21.0   .774    .816    .795    -1.993        21.0   .769    .804    .786    -2.088
 22.0   .772    .818    .795    -1.992        22.0   .769    .807    .788    -2.070
 23.0   .770    .820    .795    -1.990        23.0   .769    .811    .790    -2.052
 24.0   .768    .823    .795    -1.988        24.0   .769    .814    .791    -2.033
 25.0   .766    .825    .796    -1.987        25.0   .769    .818    .793    -2.012
 26.0   .763    .828    .796    -1.985        26.0   .769    .822    .795    -1.992
 27.0   .761    .831    .796    -1.984        27.0   .769    .826    .797    -1.970
 28.0   .758    .833    .796    -1.984        28.0   .769    .830    .799    -1.948
 29.0   .755    .836    .796    -1.983        29.0   .769    .834    .801    -1.925
 30.0   .752    .839    .796    -1.983        30.0   .769    .839    .803    -1.901
 31.0   .749    .843    .796    -1.984        31.0   .769    .843    .806    -1.877
 32.0   .746    .846    .796    -1.985        32.0   .769    .848    .808    -1.853
 33.0   .742    .849    .796    -1.986        33.0   .769    .853    .810    -1.828
 34.0   .739    .852    .795    -1.988        34.0   .768    .858    .813    -1.803
 35.0   .735    .856    .795    -1.991        35.0   .768    .863    .815    -1.779
 36.0   .731    .859    .795    -1.995        36.0   .768    .868    .817    -1.755
 37.0   .726    .862    .794    -1.999        37.0   .767    .873    .819    -1.731
 38.0   .722    .866    .794    -2.005        38.0   .766    .878    .821    -1.709
 39.0   .717    .869    .793    -2.012        39.0   .765    .883    .823    -1.687
 40.0   .712    .873    .792    -2.020        40.0   .764    .888    .825    -1.666
 41.0   .707    .876    .792    -2.030        41.0   .762    .893    .827    -1.650
 42.0   .701    .880    .791    -2.041        42.0   .760    .898    .828    -1.635
 43.0   .696    .883    .789    -2.055        43.0   .757    .903    .830    -1.624
 44.0   .690    .886    .788    -2.070        44.0   .754    .908    .830    -1.616
 45.0   .683    .890    .786    -2.087        45.0   .750    .913    .831    -1.613
 46.0   .677    .893    .785    -2.107        46.0   .745    .917    .830    -1.615
 47.0   .670    .896    .783    -2.129        47.0   .739    .921    .829    -1.624
 48.0   .663    .898    .780    -2.154        48.0   .733    .924    .828    -1.640
 49.0   .655    .901    .778    -2.183        49.0   .725    .927    .826    -1.664
 50.0   .647    .903    .775    -2.214        50.0   .717    .929    .822    -1.696
 51.0   .639    .905    .772    -2.250        51.0   .707    .931    .818    -1.742
 52.0   .630    .907    .768    -2.289        52.0   .696    .932    .813    -1.797
 53.0   .621    .908    .764    -2.333        53.0   .683    .931    .807    -1.864
 54.0   .611    .909    .760    -2.381        54.0   .670    .930    .799    -1.944
 55.0   .601    .910    .756    -2.435        55.0   .654    .928    .791    -2.039

 56.0   .591    .910    .750    -2.494        56.0   .637    .925    .781    -2.147
 57.0   .580    .910    .745    -2.558        57.0   .619    .922    .770    -2.270
 58.0   .569    .909    .739    -2.629        58.0   .600    .917    .758    -2.407
 59.0   .558    .907    .732    -2.706        59.0   .579    .912    .745    -2.557
 60.0   .546    .905    .725    -2.790        60.0   .557    .906    .731    -2.718
 61.0   .534    .903    .718    -2.881        61.0   .534    .901    .717    -2.887
 62.0   .521    .899    .710    -2.980        62.0   .511    .896    .703    -3.060
 63.0   .508    .895    .701    -3.087        63.0   .488    .891    .689    -3.232
 64.0   .494    .890    .692    -3.202        64.0   .465    .888    .676    -3.396
 65.0   .480    .884    .682    -3.326        65.0   .444    .887    .665    -3.543
 66.0   .466    .878    .671    -3.459        66.0   .425    .889    .656    -3.663
 67.0   .451    .871    .661    -3.601        67.0   .409    .894    .650    -3.744
 68.0   .437    .862    .649    -3.754        68.0   .396    .903    .647    -3.776
 69.0   .421    .853    .637    -3.916        69.0   .388    .917    .649    -3.749
 70.0   .406    .844    .624    -4.090        70.0   .383    .937    .656    -3.656
 71.0   .391    .833    .611    -4.275        71.0   .383    .964    .668    -3.499
 72.0   .375    .821    .597    -4.474        72.0   .385    .998    .685    -3.287
 73.0   .359    .807    .583    -4.687        73.0   .388   1.037    .705    -3.034
 74.0   .343    .793    .568    -4.916        74.0   .392   1.080    .727    -2.775
 75.0   .327    .776    .552    -5.169        75.0   .394   1.123    .747    -2.526
 76.0   .311    .759    .534    -5.446        76.0   .394   1.163    .765    -2.326
 77.0   .294    .737    .516    -5.753        77.0   .391   1.193    .776    -2.203
 78.0   .276    .713    .495    -6.100        78.0   .384   1.211    .778    -2.180
 79.0   .261    .686    .473    -6.498        79.0   .372   1.210    .769    -2.264
 80.0   .243    .654    .449    -6.960        80.0   .356   1.190    .747    -2.534
 81.0   .225    .617    .421    -7.502        81.0   .336   1.149    .712    -2.951
 82.0   .207    .574    .391    -8.167        82.0   .311   1.084    .664    -3.553
 83.0   .187    .524    .356    -8.976        83.0   .283   1.000    .605    -4.36[illegible]
 84.0   .166    .467    .317    -9.955        84.0   .251    .898    .527    -5.407
 85.0   .144    .401    .273   -11.265        85.0   .216    .783    .461    -6.730
 86.0   .120    .328    .224   -12.959        86.0   .179    .657    .383    -9.41[illegible]
 87.0   .094    .247    .170   -15.357        87.0   .138    .521    .295   -10.503
 88.0   .066    .167    .114   -18.696        88.0   .095    .375    .207   -13.701
 89.0   .035    .076    .055   -25.138        89.0   .049    .279    .111   -19.082
```

FIGURE 5. COMPUTER RESULTS FOR COMPLETE TRANSMISSION COEFFICIENT MAGNITUDES

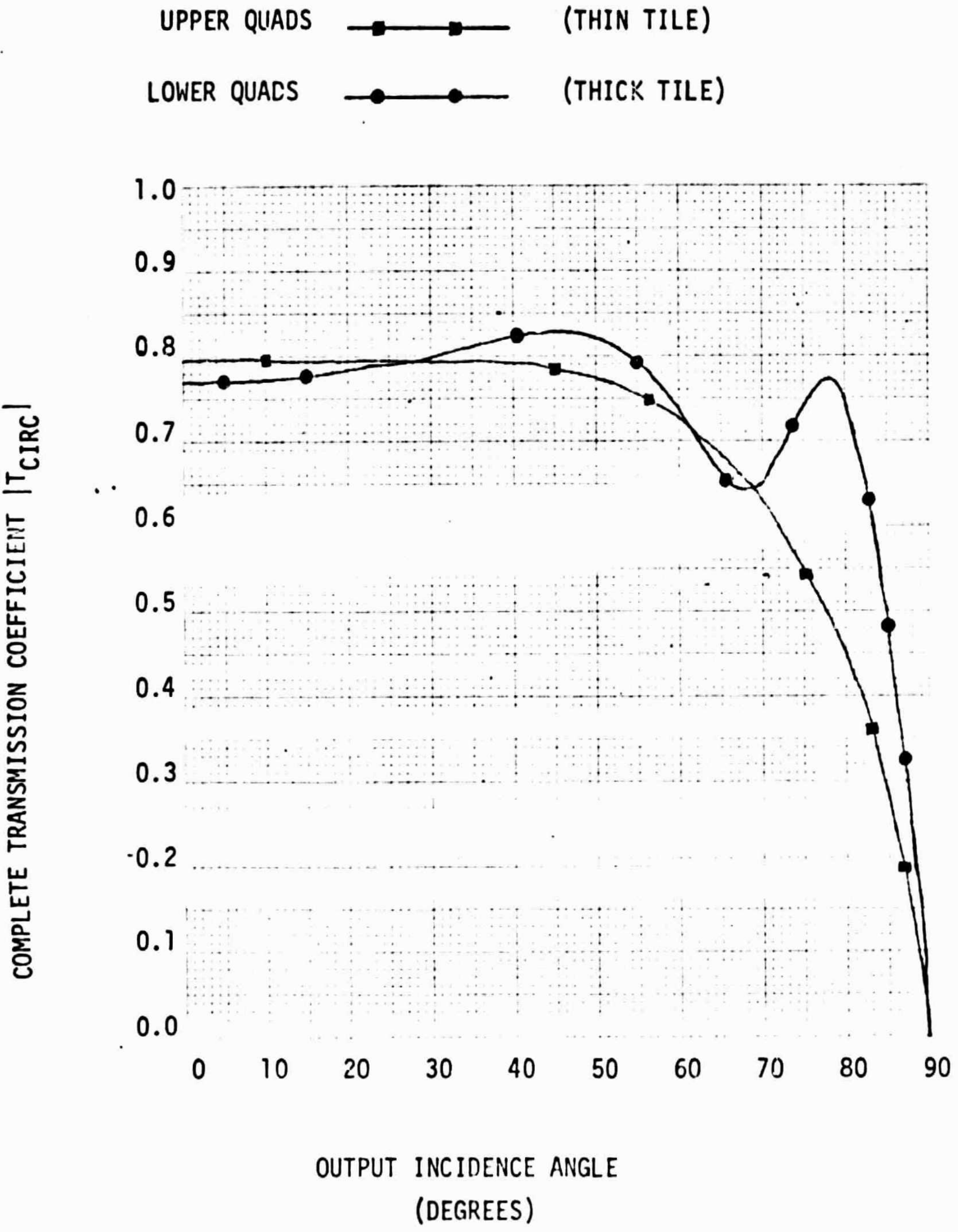


FIGURE 6. PLOT FOR COMPLETE TRANSMISSION COEFFICIENTS

It is observed from Figures 5 and 6 that the TPS has a noticeable effect on the lower Quad antennas with a slight reduction in gain on axis (normal to the antenna surface) and relative increases in gain off-axis with a maximum at Θ = 45° and Θ = 78°. The general effect of the TPS on the lower Quads will be to slightly increase the antenna beamwidth over that obtained when the antenna is operated without a TPS covering. The effect of the TPS on the upper Quads is to gradually decrease gain as the angle off-axis increases. From Θ = 0° to Θ = 45° there is little change in the level; however beyond 45° the gain level falls off significantly. The TPS in this case has the effect of narrowing the beamwidth of the upper Quads. In addition to beamwidth variation effects, the transmission coefficients for parallel polarization in Figure 5 are found to be generally larger than those for perpendicular polarization. The result is that axial ratio degradation occurs off-axis. Using Equation (22) the approximate axial ratio degradation for the upper Quads is found to be 2.9 dB at θ = 50° and 6.36 dB at θ= 70°. For the lower Quads the axial ratio degradation is found to be 2.25 dB at θ = 50° and 7.77 dB at θ = 70°. If the S-Band Quads have a lower parallel polarization components with no TPS the previous axial ratio numbers may improve. Also, since the maximum and minimum for perpendicular and parallel polarization do not occur at the same angles some unusual axial ratio variation may be expected.

5.0 CONCLUSIONS

The developed computer program shows that slight changes in beamwidth may be expected between the upper and lower Quad antennas caused by the difference in thickness of the TPS tiles. Also, a general degradation in axial ratio is shown as the off-axis angle of the Quad antenna is increased. The axial ratio degradation may be improved by using an antenna design with a less pronounced parallel polarization component when operating without a TPS cover.

This investigation shows that the multiple layer dielectric covering for the upper Quad antennas will slightly decrease the antenna beamwidth of that obtained without a TPS covering. In addition, the lower Quad patterns are slightly flattened on axis and the beamwidth is slightly increased over the no TPS condition. Since the pattern modification effects of the TPS are sensitive to changes in dielectric constant, material thickness and frequency, a change in any of these parameters will result in a different pattern modification effect which may be used to optimize the antenna coverage.

6.0 REFERENCES

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APPENDIX

LISTING FOR PROGRAM WHICH
PRODUCES DATA IN TABLE
FORM (SEE FIGURE 3)

```
      REAL IE1,IE2,IE3,IE4,IE5
      COMPLEX TPEN,XET,TPAR
      COMPLEX R0,R1,R2,R3,R4,R5,R6
      COMPLEX T01PEN,T12PEN,T23PEN,T34PEN,T45PEN,T56PEN
      COMPLEX T01PAR,T12PAR,T23PAR,T34PAR,T45PAR,T56PAR
      COMPLEX R12PEN,R23PEN,R34PEN,R45PEN,R56PEN
      COMPLEX R12PAR,R23PAR,R34PAR,R45PAR,R56PAR
      COMPLEX EC0,EC1,EC2,EC3,EC4,EC5,EC6
      COMPLEX T54PAR,T43PAR,T32PAR,T21PAR
      COMPLEX T54PEN,T43PEN,T32PEN,T21PEN
      J=0
      X4=.405
      GO TO 4
    3 X4=1.86
    4 WRITE(6,5)
    5 FORMAT(1H1,1X,8HTHETA(0),2X,8HTHETA(1),2X,8HDELAY(1),2X,8HTHETA(2)
     1,2X,8HDELAY(2),2X,8HTHETA(3),2X,8HDELAY(3),2X,8HTHETA(4),2X,8HDELA
     2Y(4),2X,8HTHETA(5),2X,8HDELAY(5),2X,8HTHETA(6))
      X1=.015
      X2=.25
      X3=.015
      X5=.01
      PI=3.14159
      E0=1.
      E1=4.0
      E2=3.0
      E3=4.0
      E4=1.17
      E5=4.0
      E6=1.0
      TD1=.005
      TD2=.04
      TD3=.005
      TD4=.0016
      TD5=.003
      IE1=-E1*TD1
      IE2=-E2*TD2
      IE3=-E3*TD3
      IE4=-E4*TD4
      IE5=-E5*TD5
      EC0=CMPLX(E0,0.0)
      EC1=CMPLX(E1,IE1)
      EC2=CMPLX(E2,IE2)
      EC3=CMPLX(E3,IE3)
      EC4=CMPLX(E4,IE4)
      EC5=CMPLX(E5,IE5)
      EC6=CMPLX(E6,0.0)
      R0=CSQRT(EC0)
      R1=CSQRT(EC1)
      R2=CSQRT(EC2)
      R3=CSQRT(EC3)
      R4=CSQRT(EC4)
      R5=CSQRT(EC5)
      R6=CSQRT(EC6)
      C=11808.
      F=2200.
```

```
      RD=180./3.14159
      DO 20 I=1,89
      T0=FLOAT(I)
C T0R - T6R REPRESENT ANGLES OF REFRACTION IN RADIANS
      T0R=T0/RD
      T1R=ASIN(SQRT(E0/E1)*SIN(T0R))
      T2R=ASIN(SQRT(E1/E2)*SIN(T1R))
      T3R=ASIN(SQRT(E2/E3)*SIN(T2R))
      T4R=ASIN(SQRT(E3/E4)*SIN(T3R))
      T5R=ASIN(SQRT(E4/E5)*SIN(T4R))
      T6R=ASIN(SQRT(E5/E6)*SIN(T5R))
      T1=T1R*RD
      T2=T2R*RD
      T3=T3R*RD
      T4=T4R*RD
      T5=T5R*RD
      T6=T6R*RD
C XE1 - XE5 REPRESENT PHASE DELAYS IN DEGREES IN EACH DIELECTRIC
      XE1=SQRT(E1)*360*F*X1/(C*COS(T1R))
      XE2=SQRT(E2)*360*F*X2/(C*COS(T2R))
      XE3=SQRT(E3)*360*F*X3/(C*COS(T3R))
      XE4=SQRT(E4)*360*F*X4/(C*COS(T4R))
      XE5=SQRT(E5)*360*F*X5/(C*COS(T5R))
C ATT1 - ATT5 REPRESENT ELECTRIC FIELD ATTENUATION FACTORS
      ATT1=(PI*F*SQRT(E1)*TAN(TD1)*X1)/(C*COS(T1R))
      ATT1=EXP(-ATT1)
      ATT2=(PI*F*SQRT(E2)*TAN(TD2)*X2)/(C*COS(T2R))
      ATT2=EXP(-ATT2)
      ATT3=(PI*F*SQRT(E3)*TAN(TD3)*X3)/(C*COS(T3R))
      ATT3=EXP(-ATT3)
      ATT4=(PI*F*SQRT(E4)*TAN(TD4)*X4)/(C*COS(T4R))
      ATT4=EXP(-ATT4)
      ATT5=(PI*F*SQRT(E5)*TAN(TD5)*X5)/(C*COS(T5R))
      ATT5=EXP(-ATT5)
      WRITE(6,10)T0,T1,XE1,T2,XE2,T3,XE3,T4,XE4,T5,XE5,T6
   10 FORMAT(12F10.1)
C T01PEN - T56PEN REPRESENT COMPLEX ELECTRIC FIELD TRANSMISSION
C                   COEFFICIENTS FOR PERPENDICULAR POLARIZATION
      T01PEN=2.*R0*COS(T0R)/(R0*COS(T0R)+R1*COS(T1R))
      T12PEN=2.*R1*COS(T1R)/(R1*COS(T1R)+R2*COS(T2R))
      T23PEN=2.*R2*COS(T2R)/(R2*COS(T2R)+R3*COS(T3R))
      T34PEN=2.*R3*COS(T3R)/(R3*COS(T3R)+R4*COS(T4R))
      T45PEN=2.*R4*COS(T4R)/(R4*COS(T4R)+R5*COS(T5R))
      T56PEN=2.*R5*COS(T5R)/(R5*COS(T5R)+R6*COS(T6R))
C T01PAR - T56PAR REPRESENT COMPLEX ELECTRIC FIELD TRANSMISSION
C                   COEFFICIENTS FOR PARALLEL POLARIZATION
      T01PAR=2.*R0*COS(T0R)/(R0*COS(T1R)+R1*COS(T0R))
      T12PAR=2.*R1*COS(T1R)/(R1*COS(T2R)+R2*COS(T1R))
      T23PAR=2.*R2*COS(T2R)/(R2*COS(T3R)+R3*COS(T2R))
      T34PAR=2.*R3*COS(T3R)/(R3*COS(T4R)+R4*COS(T3R))
      T45PAR=2.*R4*COS(T4R)/(R4*COS(T5R)+R5*COS(T4R))
      T56PAR=2.*R5*COS(T5R)/(R5*COS(T6R)+R6*COS(T5R))
C R12PEN - R56PEN REPRESENT COMPLEX ELECTRIC FIELD REFLECTION
C                   COEFFICIENTS FOR PEPPENDICULAR POLARIZATION
      R12PEN=(R1*COS(T1R)-R2*COS(T2R))/(R1*COS(T1R)+R2*COS(T2R))
      R23PEN=(R2*COS(T2R)-R3*COS(T3R))/(R2*COS(T2R)+R3*COS(T3R))
      R34PEN=(R3*COS(T3R)-R4*COS(T4R))/(R3*COS(T3R)+R4*COS(T4R))
      R45PEN=(R4*COS(T4R)-R5*COS(T5R))/(R4*COS(T4R)+R5*COS(T5R))
      R56PEN=(R5*COS(T5R)-R6*COS(T6R))/(R5*COS(T5R)+R6*COS(T6R))
C R12PAR - R56PAR REPRESENT COMPLEX ELECTRIC FIELD REFLECTION
C                   COEFFICIENTS FOR PARALLEL POLARIZATION
      R12PAR=(R1*COS(T2R)-R2*COS(T1R))/(R1*COS(T2R)+R2*COS(T1R))
      R23PAR=(R2*COS(T3R)-R3*COS(T2R))/(R2*COS(T3R)+R3*COS(T2R))
      R34PAR=(R3*COS(T4R)-R4*COS(T3R))/(R3*COS(T4R)+R4*COS(T3R))
      R45PAR=(R4*COS(T5R)-R5*COS(T4R))/(R4*COS(T5R)+R5*COS(T4R))
      R56PAR=(R5*COS(T6R)-R6*COS(T5R))/(R5*COS(T6R)+R6*COS(T5R))
C T54PEN - T21PEN REPRESENT TRANSMISSION COEFFICIENTS FOR REFLECTED
C                   RAYS WITH PERPENDICULAR POLARIZATION
      T54PEN=2.*R5*COS(T5R)/(R5*COS(T5R)+R4*COS(T4R))
      T43PEN=2.*R4*COS(T4R)/(R4*COS(T4R)+R3*COS(T3R))
```

```
      T32PEN=2.*R3*COS(T3R)/(R3*COS(T3R)+R2*COS(T2R))
      T21PEN=2.*R2*COS(T2R)/(R2*COS(T2R)+R1*COS(T1R))
C T54PAR - T21PAR REPRESENT TRANSMISSION COEFFICIENTS FOR REFLECTED
C                     RAYS WITH PARALLEL POLARIZATION
      T54PAR=2.*R5*COS(T5R)/(R5*COS(T4R)+R4*COS(T5R))
      T43PAR=2.*R4*COS(T4R)/(R4*COS(T3R)+R3*COS(T4R))
      T32PAR=2.*R3*COS(T3R)/(R3*COS(T2R)+R2*COS(T3R))
      T21PAR=2.*R2*COS(T2R)/(R2*COS(T1R)+R1*COS(T2R))
      T01PE=CABS(T01PEN)
      T12PE=CABS(T12PEN)
      T23PE=CABS(T23PEN)
      T34PE=CABS(T34PEN)
      T45PE=CABS(T45PEN)
      T56PE=CABS(T56PEN)
      T01PA=CABS(T01PAR)
      T12PA=CABS(T12PAR)
      T23PA=CABS(T23PAR)
      T34PA=CABS(T34PAR)
      T45PA=CABS(T45PAR)
      T56PA=CABS(T56PAR)
      R12PE=CABS(R12PEN)
      R23PE=CABS(R23PEN)
      R34PE=CABS(R34PEN)
      R45PE=CABS(R45PEN)
      R56PE=CABS(R56PEN)
      R12PA=CABS(R12PAR)
      R23PA=CABS(R23PAR)
      R34PA=CABS(R34PAR)
      R45PA=CABS(R45PAR)
      R56PA=CABS(R56PAR)
      T54PE=CABS(T54PEN)
      T43PE=CABS(T43PEN)
      T32PE=CABS(T32PEN)
      T21PE=CABS(T21PEN)
      T54PA=CABS(T54PAR)
      T43PA=CABS(T43PAR)
      T32PA=CABS(T32PAR)
      T21PA=CABS(T21PAR)
      XETT=(XE1+XE2+XE3+XE4+XE5)/RD
      XET=CMPLX(0.0,-XETT)
      TPEN=T01PEN*T12PEN*T23PEN*T34PEN*T45PEN*T56PEN*ATT1*ATT2*ATT3*ATT4
     1*ATT5*CEXP(XET)
      TPE=CABS(TPEN)
      TPAR=T01PAR*T12PAR*T23PAR*T34PAR*T45PAR*T56PAR*ATT1*ATT2*ATT3*ATT4
     1*ATT5*CEXP(XET)
      TPA=CABS(TPAR)
      WRITE(6,15)T01PE,T12PE,T23PE,T34PE,T45PE,T56PE
      WRITE(6,15)T01PA,T12PA,T23PA,T34PA,T45PA,T56PA
      WRITE(6,18)R12PE,R23PE,R34PE,R45PE,R56PE
      WRITE(6,18)R12PA,R23PA,R34PA,R45PA,R56PA
      WRITE(6,19)T21PE,T32PE,T43PE,T54PE
      WRITE(6,19)T21PA,T32PA,T43PA,T54PA
      WRITE(6,18)ATT1,ATT2,ATT3,ATT4,ATT5
      WRITE(6,25)TPE
      WRITE(6,25)TPA
   15 FORMAT(10X,F5.2,5(15X,F5.2))
   18 FORMAT(30X,F5.2,4(15X,F5.2))
   19 FORMAT(30X,F5.2,3(15X,F5.2))
   25 FORMAT(120X,F5.4)
   20 CONTINUE
      J=J+1
      IF(J.EQ.1) GO TO 3
      END
```

ORIGINAL PAGE IS
OF POOR QUALITY

LISTING FOR PROGRAM
WHICH INCLUDES MULTIPLE
INTERNAL REFLECTIONS
TO PRODUCE COMPLETE TRANSMISSION
COEFFICIENTS (SEE FIGURE 6)

```
      REAL IE1,IE2,IE3,IE4,IE5
      COMPLEX TPEN,XET,TPAR
      COMPLEX R0,R1,R2,R3,R4,R5,R6
      COMPLEX T01PEN,T12PEN,T23PEN,T34PEN,T45PEN,T56PEN
      COMPLEX T01PAR,T12PAR,T23PAR,T34PAR,T45PAR,T56PAR
      COMPLEX R12PEN,R23PEN,R34PEN,R45PEN,R56PEN
      COMPLEX R12PAR,R23PAR,R34PAR,R45PAR,R56PAR
      COMPLEX EC0,EC1,EC2,EC3,EC4,EC5,EC6
      COMPLEX T54PAR,T43PAR,T32PAR,T21PAR
      COMPLEX T54PEN,T43PEN,T32PEN,T21PEN
      COMPLEX TPENOT,TPARAT,TCIR
      COMPLEX TR56PE,TR56PA,TR45PE,TR45PA,TR34PE,TR34PA
      COMPLEX T546PE,T546PA,T446PE,T446PA
      COMPLEX T556PE,T556PA
      COMPLEX X546,X446,X556
      COMPLEX XETR45,XETR34
      COMPLEX XC1,XC2,XC3,XC4,XC5
      COMPLEX T255PE,T255PA,T355PE,T355PA
      COMPLEX TR23PE,TR23PA,TR12PE,TR12PA
      COMPLEX TX34PE,TX34PA,TX45PE,TX45PA,TX56PE,TX56PA
      J=0
C THICKNESS FOR UPPER QUADS
      X4=.405
      GO TO 4
C THICKNESS FOR LOWER QUADS
    3 X4=1.86
    4 WRITE(6,5)
    5 FORMAT(1H1,10X,5HTHETA,6X,3HTPE,7X,3HTPA,6X,4HTCIR,6X,8HTCIR(DB)/)
C
C X1 - X5 REPRESENT DIELECTRIC LAYER THICKNESSES
      X1=.015
      X2=.25
      X3=.015
      X5=.01
      PI=3.14159
C
C E0 - E6 REPRESENT RELATIVE DIELECTRIC CONSTANTS
      E0=1.
      E1=4.0
      E2=3.6
      E3=4.0
      E4=1.17
      E5=4.9
      E6=1.0
C TD1 - TD5 REPRESENT LOSS TANGENTS
      TD1=.005
      TD2=.04
      TD3=.005
```

```
      TD4=.0016
      TD5=.003
C IE1 - IE5 REPRESENT IMAGINARY PARTS OF RELATIVE COMPLEX PERMITTIVITIES
      IE1=-E1*TD1
      IE2=-E2*TD2
      IE3=-E3*TD3
      IE4=-E4*TD4
      IE5=-E5*TD5
C EC0 - EC6 REPRESENT RELATIVE COMPLEX PERMITTIVITIES
      EC0=CMPLX(E0,0.0)
      EC1=CMPLX(E1,IE1)
      EC2=CMPLX(E2,IE2)
      EC3=CMPLX(E3,IE3)
      EC4=CMPLX(E4,IE4)
      EC5=CMPLX(E5,IE5)
      EC6=CMPLX(E6,0.0)
C R0 - R6 REPRESENTS THE RELATIVE REFRACTION INDICES
      R0=CSQRT(EC0)
      R1=CSQRT(EC1)
      R2=CSQRT(EC2)
      R3=CSQRT(EC3)
      R4=CSQRT(EC4)
      R5=CSQRT(EC5)
      R6=CSQRT(EC6)
C     C IS THE SPEED OF LIGHT IN MEGAINCHES/SEC
      C=11808.
C F IS FREQUENCY IN MEGAHERTZ
      F=2200.
C RD CONVERTS RADIANS TO DEGREES
      RD=180./3.14159
      DO 20 I=1,89
      T0=FLOAT(I)
C
C T0R - T6R REPRESENT ANGLES OF REFRACTION IN RADIANS
      T0R=T0/RD
      T1R=ASIN(SQRT(E0/E1)*SIN(T0R))
      T2R=ASIN(SQRT(E1/E2)*SIN(T1R))
      T3R=ASIN(SQRT(E2/E3)*SIN(T2R))
      T4R=ASIN(SQRT(E3/E4)*SIN(T3R))
      T5R=ASIN(SQRT(E4/E5)*SIN(T4R))
      T6R=ASIN(SQRT(E5/E6)*SIN(T5R))
C T0 -T6  REPRESENT ANGLES OF REFRACTION IN DEGREES
      T1=T1R*RD
      T2=T2R*RD
      T3=T3R*RD
      T4=T4R*RD
      T5=T5R*RD
      T6=T6R*RD
C XE1 - XE5 REPRESENT PHASE DELAYS IN DEGREES IN EACH DIELECTRIC
      XE1=SQRT(E1)*360*F*X1/(C*COS(T1R))
      XE2=SQRT(E2)*360*F*X2/(C*COS(T2R))
      XE3=SQRT(E3)*360*F*X3/(C*COS(T3R))
      XE4=SQRT(E4)*360*F*X4/(C*COS(T4R))
      XE5=SQRT(E5)*360*F*X5/(C*COS(T5R))
C
C XR1 - XR5 REPRESENT PHASE DELAYS IN RADIANS IN EACH DIELECTRIC
      XR1=XE1/RD
```

```
      XR2=XE2/RD
      XR3=XE3/RD
      XR4=XE4/RD
      XR5=XE5/RD
C XC1 - XC5 REPRESENT PHASE DELAYS IN RADIANS EXPRESSED AS A CMPLX NO.
      XC1=CMPLX(0.0,-XR1)
      XC2=CMPLX(0.0,-XR2)
      XC3=CMPLX(0.0,-XR3)
      XC4=CMPLX(0.0,-XR4)
      XC5=CMPLX(0.0,-XR5)
C ATT1 - ATT5 REPRESENT ELECTRIC FIELD ATTENUATION FACTORS
      ATT1=EXP(-1.*(PI*F*SQRT(E1)*TAN(TD1)*X1)/(C*COS(T1R)))
      ATT2=EXP(-1.*(PI*F*SQRT(E2)*TAN(TD2)*X2)/(C*COS(T2R)))
      ATT3=EXP(-1.*(PI*F*SQRT(E3)*TAN(TD3)*X3)/(C*COS(T3R)))
      ATT4=EXP(-1.*(PI*F*SQRT(E4)*TAN(TD4)*X4)/(C*COS(T4R)))
      ATT5=EXP(-1.*(PI*F*SQRT(E5)*TAN(TD5)*X5)/(C*COS(T5R)))
C T01PEN - T56PEN REPRESENT COMPLEX ELECTRIC FIELD TRANSMISSION
C                  COEFFICIENTS FOR PERPENDICULAR POLARIZATION
      T01PEN=2.*R0*COS(T0R)/(R0*COS(T0R)+R1*COS(T1R))
      T12PEN=2.*R1*COS(T1R)/(R1*COS(T1R)+R2*COS(T2R))
      T23PEN=2.*R2*COS(T2R)/(R2*COS(T2R)+R3*COS(T3R))
      T34PEN=2.*R3*COS(T3R)/(R3*COS(T3R)+R4*COS(T4R))
      T45PEN=2.*R4*COS(T4R)/(R4*COS(T4R)+R5*COS(T5R))
      T56PEN=2.*R5*COS(T5R)/(R5*COS(T5R)+R6*COS(T6R))
C T01PAR - T56PAR REPRESENT COMPLEX ELECTRIC FIELD TRANSMISSION
C                  COEFFICIENTS FOR PARALLEL POLARIZATION
      T01PAR=2.*R0*COS(T0R)/(R0*COS(T1R)+R1*COS(T0R))
      T12PAR=2.*R1*COS(T1R)/(R1*COS(T2R)+R2*COS(T1R))
      T23PAR=2.*R2*COS(T2R)/(R2*COS(T3R)+R3*COS(T2R))
      T34PAR=2.*R3*COS(T3R)/(R3*COS(T4R)+R4*COS(T3R))
      T45PAR=2.*R4*COS(T4R)/(R4*COS(T5R)+R5*COS(T4R))
      T56PAR=2.*R5*COS(T5R)/(R5*COS(T6R)+R6*COS(T5R))
C R12PEN - R56PEN REPRESENT COMPLEX ELECTRIC FIELD REFLECTION
C                  COEFFICIENTS FOR PERPENDICULAR POLARIZATION
      R12PEN=(R1*COS(T1R)-R2*COS(T2R))/(R1*COS(T1R)+R2*COS(T2R))
      R23PEN=(R2*COS(T2R)-R3*COS(T3R))/(R2*COS(T2R)+R3*COS(T3R))
      R34PEN=(R3*COS(T3R)-R4*COS(T4R))/(R3*COS(T3R)+R4*COS(T4R))
      R45PEN=(R4*COS(T4R)-R5*COS(T5R))/(R4*COS(T4R)+R5*COS(T5R))
      R56PEN=(R5*COS(T5R)-R6*COS(T6R))/(R5*COS(T5R)+R6*COS(T6R))
C R12PAR - R56PAR REPRESENT COMPLEX ELECTRIC FIELD REFLECTION
C                  COEFFICIENTS FOR PARALLEL POLARIZATION
      R12PAR=(R1*COS(T2R)-R2*COS(T1R))/(R1*COS(T2R)+R2*COS(T1R))
      R23PAR=(R2*COS(T3R)-R3*COS(T2R))/(R2*COS(T3R)+R3*COS(T2R))
      R34PAR=(R3*COS(T4R)-R4*COS(T3R))/(R3*COS(T4R)+R4*COS(T3R))
      R45PAR=(R4*COS(T5R)-R5*COS(T4R))/(R4*COS(T5R)+R5*COS(T4R))
      R56PAR=(R5*COS(T6R)-R6*COS(T5R))/(R5*COS(T6R)+R6*COS(T5R))
C T54PEN - T21PEN REPRESENT TRANSMISSION COEFFICIENTS FOR REFLECTED
C                  RAYS WITH PERPENDICULAR POLARIZATION
      T54PEN=2.*R5*COS(T5R)/(R5*COS(T5R)+R4*COS(T4R))
      T43PEN=2.*R4*COS(T4R)/(R4*COS(T4R)+R3*COS(T3R))
      T32PEN=2.*R3*COS(T3R)/(R3*COS(T3R)+R2*COS(T2R))
      T21PEN=2.*R2*COS(T2R)/(R2*COS(T2R)+R1*COS(T1R))
C T54PAR - T21PAR REPRESENT TRANSMISSION COEFFICIENTS FOR REFLECTED
C                  RAYS WITH PARALLEL POLARIZATION
      T54PAR=2.*R5*COS(T5R)/(R5*COS(T4R)+R4*COS(T5R))
      T43PAR=2.*R4*COS(T4R)/(R4*COS(T3R)+R3*COS(T4R))
      T32PAR=2.*R3*COS(T3R)/(R3*COS(T2R)+R2*COS(T3R))
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      T21PAR=2.*R2*COS(T2R)/(R2*COS(T1R)+R1*COS(T2R))
C
C XETT REPRESENTS PHASE DELAYS IN RADIANS THRU 5 TPS MATERIALS
      XETT=(XE1+XE2+XE3+XE4+XE5)/RD
      XET=CMPLX(0.0,-XETT)
C
C TPEN REPRESENTS DIRECT TRANSMISSION COEFFICIENT FOR PERPENDICULAR
C      POLARIZATION
      TPEN=T01PEN*T12PEN*T23PEN*T34PEN*T45PEN*T56PEN*ATT1*ATT2*ATT3*ATT4
     1*ATT5*CEXP(XET)
C
C TPAR REPRESENTS DIRECT TRANSMISSION COEFFICIENT  FOR PARALLEL
C      POLARIZATION
      TPAR=T01PAR*T12PAR*T23PAR*T34PAR*T45PAR*T56PAR*ATT1*ATT2*ATT3*ATT4
     1*ATT5*CEXP(XET)
C
C TR56PE REPRESENTS TRANSMISSION COEFFICIENT FOR RAY REFLECTED FROM
C       THE 5/6 INTERFACE AND FROM THE METAL GROUND PLANE WITH
C       PERPENDICULAR POLARIZATION
      TR56PE=T01PEN*T12PEN*T23PEN*T34PEN*T45PEN*R56PEN*T54PEN*T43PEN*T32
     1PEN*T21PEN*-1.*T12PEN*T23PEN*T34PEN*T45PEN*T56PEN*((ATT1*ATT2*ATT3
     2*ATT4*ATT5)**(3.0))*CEXP(3.*XET)
C TR56PA REPRESENTS TRANSMISSION COEFFICIENT FOR RAY REFLECTED FROM
C       THE 5/6 INTERFACE AND FROM THE METAL GROUND PLANE WITH
C       PARALLEL POLARIZATION
      TR56PA=T01PAR*T12PAR*T23PAR*T34PAR*T45PAR*R56PAR*T54PAR*T43PAR*T32
     1PAR*T21PAR*-1.*T12PAR*T23PAR*T34PAR*T45PAR*T56PAR*((ATT1*ATT2*ATT3
     2*ATT4*ATT5)**(3.0))*CEXP(3.*XET)
      XTR45=(3.*(XE1+XE2+XE3+XE4)+XE5)/RD
C XETR45 REPRESENTS PHASE DELAY IN RADIANS FOR REFLECTION FROM THE 4/5
C       INTERFACE AND REREFLECTION FROM THE METAL GROUND PLANE
      XETR45=CMPLX(0.0,-XTR45)
C TR45PE REPRESENTS TRANSMISSION COEFFICIENT FOR RAY REFLECTED FROM
C       THE 4/5 INTERFACE AND FROM THE METAL GROUND PLANE WITH
C       PERPENDICULAR POLARIZATION
      TR45PE=T01PEN*T12PEN*T23PEN*T34PEN*R45PEN*T43PEN*T32PEN*T21PEN*-1.
     1*T12PEN*T23PEN*T34PEN*T45PEN*T56PEN*((ATT1*ATT2*ATT3*ATT4)**(2.))*
     2ATT1*ATT2*ATT3*ATT4*ATT5*CEXP(XETR45)
C
C TR45PA REPRESENTS TRANSMISSION COEFFICIENT FOR RAY REFLECTED FROM
C       THE 4/5 INTERFACE AND FROM THE METAL GROUND PLANE WITH
C       PARALLEL POLARIZATION
      TR45PA=T01PAR*T12PAR*T23PAR*T34PAR*R45PAR*T43PAR*T32PAR*T21PAR*-1.
     1*T12PAR*T23PAR*T34PAR*T45PAR*T56PAR*((ATT1*ATT2*ATT3*ATT4)**(2.))*
     2*ATT1*ATT2*ATT3*ATT4*ATT5*CEXP(XETR45)
      XTR34=(3.*(XE1+XE2+XE3)+XE4+XE5)/RD
C
C
C XETR34 REPRESENTS PHASE DELAY IN RADIANS FOR REFLECTION FROM THE 3/4
C       INTERFACE AND REREFLECTION FROM THE METAL GROUND PLANE
      XETR34=CMPLX(0.0,-XTR34)
C
C
C TR34PE REPRESENTS TRANSMISSION COEFFICIENT FOR RAY REFLECTED FROM
C       THE 3/4 INTERFACE AND FROM THE METAL GROUND PLANE WITH
C       PERPENDICULAR POLARIZATION
      TR34PE=T01PEN*T12PEN*T23PEN*R34PEN*T32PEN*T21PEN*-1.*T12PEN*T23PEN
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     1*T34PEN*T45PEN*T56PEN*((ATT1*ATT2*ATT3)**(2.))*ATT1*ATT2*ATT3*ATT4
     2*ATT5*CEXP(XETR34)
C
C
C TR34PA REPRESENTS TRANSMISSION COEFFICIENT FOR RAY REFLECTED FROM
C        THE 3/4 INTERFACE AND FROM THE METAL GROUND PLANE WITH
C        PARALLEL POLARIZATION
      TR34PA=T01PAR*T12PAR*T23PAR*R34PAR*T32PAR*T21PAR*-1.*T12PAR*T23PAR
     1*T34PAR*T45PAR*T56PAR*((ATT1*ATT2*ATT3)**(2.))*ATT1*ATT2*ATT3*ATT4
     2*ATT5*CEXP(XETR34)
C
C
C TR23PE REPRESENTS TRANSMISSION COEFFICIENT FOR RAY REFLECTED FROM
C        THE 2/3 INTERFACE AND FROM THE METAL GROUND PLANE WITH
C        PERPENDICULAR POLARIZATION
      TR23PE=TPEN*T12PEN*R23PEN*T21PEN*(-1.)*((ATT1*ATT2)**2.)*CEXP(2.*(
     1XC1+XC2))
C
C
C TR23PA REPRESENTS TRANSMISSION COEFFICIENT FOR RAY REFLECTED FROM
C        THE 2/3 INTERFACE AND FROM THE  METAL GROUND PLANE WITH
C        PARALLEL POLARIZATION
      TR23PA=TPAR*T12PAR*R23PAR*T21PEN*(-1.)*((ATT1*ATT2)**2.)*CEXP(2.*(
     1XC1+XC2))
C
C
C TR12PE REPRESENTS TRANSMISSION COEFFICIENT FOR RAY REFLECTED FROM
C        THE 1/2 INTERFACE AND FROM THE  METAL GROUND PLANE WITH
C        PERPENDICULAR POLARIZATION
      TR12PE=TPEN*R12PEN*(-1.)*ATT1*ATT1*CEXP(2.*XC1)
C
C
C TR12PA REPRESENTS TRANSMISSION COEFFICIENT FOR RAY REFLECTED FROM
C        THE 1/2 INTERFACE AND FROM THE  METAL GROUND PLANE WITH
C        PARALLEL POLARIZATION
      TR12PA=TPAR*R12PAR*(-1.)*ATT1*ATT1*CEXP(2.*XC1)
      XW546=(XE1+XE2+XE3+2.*(XE4+XE5))/RD
      X546=CMPLX(0.0,-XW546)
C
C T546PE IS THE TRANSMISSION COEFFICIENT FOR THE RAY REFLCTING FROM THE
C        5/6 INTERFACE AND REFELECTING FROM THE 4/3 INTERFACE WITH
C        PERPENDICULAR POLARIZATION
      T546PE=T01PEN*T12PEN*T23PEN*T34PEN*T45PEN*R56PEN*T54PEN*T43PEN*(-R
     134PEN)*T45PEN*T56PEN*ATT1*ATT2*ATT3*((ATT4*ATT5)**(3.))*CEXP(X546)
C
C T546PA IS THE TRANSMISSION COEFFICIENT FOR THE RAY REFLCTING FROM THE
C        5/6 INTERFACE AND REFELECTING FROM THE 4/3 INTERFACE WITH
C        PARALLEL POLARIZATION
      T546PA=T01PAR*T12PAR*T23PAR*T34PAR*T45PAR*R56PAR*T54PAR*T43PAR*(-R
     134PAR)*T45PAR*T56PAR*ATT1*ATT2*ATT3*((ATT4*ATT5)**(3.))*CEXP(X546)
      XW446=(XE1+XE2+XE3+2.*XE4+XE5)/RD
      X446=CMPLX(0.0,-XW446)
C
C T446PE IS THE TRANSMISSION COEFFICIENT FOR THE RAY WITH ONE INTERNAL
C        REFLECTION IN THE 4TH LAYER WITH PERPENDICULAR POLARIZATION
      T446PE=T01PEN*T12PEN*T23PEN*T34PEN*R45PEN*(-R34PEN)*T45PEN*T56PEN*
     1ATT1*ATT2*ATT3*(ATT4**(3.))*ATT5*CEXP(X446)
```

```
C
C T446PA IS THE TRANSMISSION COEFFICIENT FOR THE RAY WITH ONE INTERNAL
C           REFLECTION IN THE 4TH LAYER WITH PARALLEL POLARIZATION
      T446PA=T01PAR*T12PAR*T23PAR*T34PAR*R45PAR*(-R34PAR)*T45PAR*T56PAR*
     1ATT1*ATT2*ATT3*(ATT4**(3.))*ATT5*CEXP(X446)
      XW556=(XE1+XE2+XE3+XE4+3.*XE5)/RD
      X556=CMPLX(0.0,-XW556)
C
C
C T556PE IS THE TRANSMISSION COEFFICIENT FOR THE RAY WITH ONE INTERNAL
C           REFLECTION IN THE 5TH LAYER WITH PERPENDICULAR POLARIZATION
      T556PE=T01PEN*T12PEN*T23PEN*T34PEN*T45PEN*R56PEN*(-1.)*R45PEN*T56P
     1EN*ATT1*ATT2*ATT3*ATT4*(ATT5**(3.))*CEXP(X556)
C
C
C T556PA IS THE TRANSMISSION COEFFICIENT FOR THE RAY WITH ONE INTERNAL
C           REFLECTION IN THE 5TH LAYER WITH PARALLEL POLARIZATION
      T556PA=T01PAR*T12PAR*T23PAR*T34PAR*T45PAR*R56PAR*(-1.)*R45PAR*T56P
     1AR*ATT1*ATT2*ATT3*ATT4*(ATT5**(3.))*CEXP(X556)
C
C
C T255PE IS THE TRANSMISSION COEFFICIENT FOR THE RAY WITH TWO INTERNAL
C           REFLECTIONS IN THE 5TH LAYER WITH PERPENDICULAR POLARIZATION
      T255PE=T556PE*R56PEN*(-R45PEN)*ATT5*ATT5*CEXP(2.*XC5)
C
C
C T255PA IS THE TRANSMISSION COEFFICIENT FOR THE RAY WITH TWO INTERNAL
C           REFLECTIONS IN THE 5TH LAYER WITH PARALLEL POLARIZATION
      T255PA=T556PE*R56PAR*(-R45PAR)*ATT5*ATT5*CEXP(2.*XC5)
C
C
C T355PE IS THE TRANSMISSION COEFFICIENT FOR THE RAY WITH THREE INTERNAL
C           REFLECTIONS IN THE 5TH LAYER WITH PERPENDICULAR POLARI3ATION
      T355PE=T255PE*R56PEN*(-R45PEN)*ATT5*ATT5*CEXP(2.*XC5)
C
C
C T355PA IS THE TRANSMISSION COEFFICIENT FOR THE RAY WITH THREE INTERNAL
C           REFLECTIONS IN THE 5TH LAYER WITH PARALLEL POLARIZATION
      T355PA=T255PA*R56PAR*(-R45PAR)*ATT5*ATT5*CEXP(2.*XC5)
C
C TX34PE REPRESENT REREFLECTION OF RAYS TR34PE+TR45PE+TR56PE FROM 3/4
C           INTERFACE AND METAL GROUND PLANE FOR PERPENDICULAR POLARIZATION
      TX34PE=(TR34PE+TR45PE+TR56PE)*R34PEN*T32PEN*T21PEN*(-1.)*T12PEN*T2
     13PEN*((ATT1*ATT2*ATT3)**2.)*CEXP(2.*(XC1+XC2+XC3))
C
C TX34PA SAME AS TX34PE EXCEPT PARALLEL POLARIZATION COMPONENTS
      TX34PA=(TR34PA+TR45PA+TR56PA)*R34PAR*T32PAR*T21PAR*(-1.)*T12PAR*T2
     13PAR*((ATT1*ATT2*ATT3)**2.)*CEXP(2.*(XC1+XC2+XC3))
C
C TX45PE SAME AS TX34PE EXCEPT REREFLECTION FROM 4/5 INTERFACE
      TX45PE=(TR34PE+TR45PE+TR56PE)*R45PEN*T43PEN*T32PEN*T21PEN*(-1.)*T1
     12PEN*T23PEN*T34PEN*((ATT1*ATT2*ATT3*ATT4)**2.)*CEXP(2.*(XC1+XC2+XC
     23+XC4))
C
C TX45PA SAME AS TX34PA EXCEPT REREFLECTION FROM 4/5 INTERFACE
      TX45PA=(TR34PA+TR45PA+TR56PA)*R45PAR*T43PAR*T32PAR*T21PAR*(-1.)*T1
     12PAR*T23PAR*T34PAR*((ATT1*ATT2*ATT3*ATT4)**2.)*CEXP(2.*(XC1+XC2+XC
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      23*XC4))
C
C TX56PE SAME AS TX34PE EXCEPT REREFLECTION FROM 5/6 INTERFACE
      TX56PE=(TR34PE+TR45PE+TR56PE)*R56PEN*T54PEN*T43PEN*T32PEN*T21PEN*(
     1-1.)*T12PEN*T23PEN*T34PEN*T45PEN*((ATT1*ATT2*ATT3*ATT4*ATT5)**2.)*
     2CEXP(2.*(XC1+XC2+XC3+XC4+XC5))
C
C TX56PA SAME AS TX34PA EXCEPT REREFLECTION FROM 5/6 INTERFACE
      TX56PA=(TR34PA+TR45PA+TR56PA)*R56PAR*T54PAR*T43PAR*T32PAR*T21PAR*(
     1-1.)*T12PAR*T23PAR*T34PAR*T45PAR*((ATT1*ATT2*ATT3*ATT4*ATT5)**2.)*
     2CEXP(2.*(XC1+XC2+XC3+XC4+XC5))
C
C TPENDT IS THE TOTAL TRANSMISSION COEFFICIENT FOR THE SUM OF ALL
C          RAYS WITH PERPENDICULAR POLARIZATION
      TPENDT=TPEN+TR56PE+TR45PE+TR34PE+T546PE+T4   PE+T556PE
     1+T255PE+T355PE
     2+TR12PE+TR23PE+TX34PE+TX45PE+TX56PE
C
C TPARAT IS THE TOTAL TRANSMISSION COEFFICIENT FOR THE SUM OF ALL
C          RAYS WITH PARALLEL POLARIZATION
      TPARAT=TPAR+TR56PA+TR45PA+TR34PA+T546PA+T446PA+T556PA
     1+T255PA+T355PA
     2+TR12PA+TR23PA+TX34PA+TX45PA+TX56PA
C
C TPE REPRESENTS THE MAGNITUDE OF THE TOTAL PERPENDICULAR TRANSMISSION
C       COEFFICIENT
      TPE=CABS(TPENDT)
C
C TPA REPRESENTS THE MAGNITUDE OF THE TOTAL PARALLEL TRANSMISSION
C       COEFFICIENT
      TPA=CABS(TPARAT)
C
C   TC1R IS THE TOTAL TRANSMISSION COEFFICIENT FOR THE SUM OF ALL
C          RAYS WITH CIRCULAR POLARIZATION
      TC1R=(TPENDT+TPARAT)/2
      TCIRCV=CABS(TC1R)
C
C DB REPRESENTS A DECIBEL FACTOR FOR CIRCULAR POLARIZATION
      DB=20.*ALOG10(TCIRCV)
      WRITE(6,50)[illegible],TPE,TPA,TCIRCV,DB
   50 FORMAT(5X,F10.1,5X,F5.3,5X,F5.3,5X,F5.3,5X,F7.3)
   20 CONTINUE
      J=J+1
      IF(J.EQ.1) GO TO 3
      END
```